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The Egg Nebula (AFGL 2688): Deepening Enigma

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Abstract.
Recent observations of the Egg Nebula (AFGL 2688), obtained at ever-increasing spatial and spectral resolution, have revealed a perplexing array of phenomena. Many of these phenomena present challenges to our understanding of this object as an emerging, bipolar planetary nebula. Here, we consider two particularly intriguing aspects of the Egg: the peculiar structure and kinematics of its equatorial regions, and the nature of an apparent widely separated companion to the central star. In the first case, we use recently acquired *Hubble Space Telescope* images to demonstrate that the H_2 emission distributed east and west of the central star is spatially coincident with a dusty, equatorial disk or torus. The H_2 is thus constrained to lie near the equatorial plane, casting doubt on pure radial outflow models for the equatorial kinematics. In the second case, we show that the apparent companion ("Peak A") may be an accreting white dwarf that has undergone one or more thermonuclear bursts.

1. Key Problems Posed by the Egg

The Egg Nebula (AFGL 2688) has long been regarded as exemplary of objects in transition from asymptotic giant branch (AGB) star to bipolar planetary nebula (PN). Recent optical, infrared, and radio observations at high spatial and spectral resolution have revealed a remarkable degree of complexity in this object (for a brief synopsis, see Kastner et al. 2002). We examine here two particularly puzzling and controversial aspects of AFGL 2688 that may provide clues to the origin of axial symmetry in PNs and proto-PNs.

1. An equatorial velocity gradient of magnitude $\sim 10-20$ km s^{-1} — similar to that observed along the polar axis — has been detected in various molecular tracers. This gradient has been attributed both to multiple, radial outflows (Cox et al. 2000) and to a component of azimuthal velocity (i.e., rotation about the polar axis; Kastner et al. 2001). Each model has problems. The "pure radial outflow" model does not appear viable if the emitting molecular gas is indeed confined to the equatorial plane, while the "rotation" model requires an

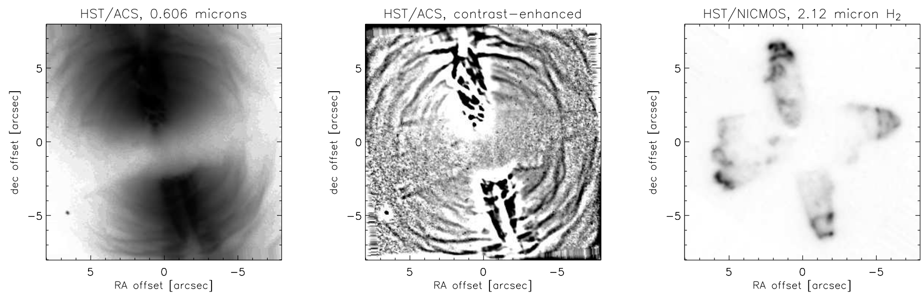

Figure 1. Left: Central region of HST/ACS 0.606 μm image of AFGL 2688. RA, dec offsets are with respect to the approximate position of the central source of illumination. Center: the same image, processed via an unsharp masking technique (following Sahai & Trauger 1998). Right: HST/NICMOS 2.12 μm image of H_2 emission from AFGL 2688 (Sahai et al. 1998).

extremely (untenably?) large reservoir of angular momentum.
2. Near-infrared polarimetric imaging suggests that a luminous source of direct emission lies embedded very near ($\sim 0.5''$ from) the central, illuminating star. This object therefore likely constitutes a widely separated ($a \approx 500$ AU) companion (Sahai et al. 1998; Weintraub et al. 2000), although Goto et al. (2002) argue, on the basis of infrared spectroscopy, that the source is instead a knot of reflecting dust.

2. The Equatorial Region: New Revelations from HST

Recently acquired *Hubble Space Telescope* (HST) images of AFGL 2688, obtained during tests of the new Advanced Camera for Surveys (ACS) in 2002 October, appear to shed new light on the structure of the equatorial region of the nebula. The images were obtained with the ACS Wide Field Camera (WFC) through polarimetric filters and a broad-band filter centered at 0.606 μm; the pixel scale of the WFC is $0.05''$ pixel^{-1}. Here, we have averaged the polarized images to form a single, total intensity image of AFGL 2688.

The left panel of Fig. 1 displays the central region of AFGL 2688 in the ACS/WFC image. These images reveal, in unprecedented detail, fine structure in the "dark lane" that marks the equatorial plane of the system. Of particular note is the sharp, sculpted southern boundary of the dark lane. This appearance suggests that the inner region of the southern reflection lobe is being occulted by material that is largely confined to the equatorial plane. *Provided that the equatorial regions harbor a dusty disk or torus that is several arcsec (thousands of AU) in radius,* such occultation is a natural consequence of the fact that the

north lobe is pointed slightly toward, and the south lobe slightly away from, the observer (Sahai et al. 1998, Kastner et al. 2001, and references therein).

The processed image in the center panel of Fig. 1 emphasizes the fine structure in the equatorial regions and, in particular, reveals the faint outline of the equatorial torus. The outline of the torus is most apparent along the sharp southern edge of the dark lane, but also appears as a linear feature extending "behind" the inner north lobe. The latter feature could be interpreted as the outline of the rear-facing edge of the equatorial disk of AFGL 2688.

There is a dramatic correspondence between the faint outline of the equatorial torus in the ACS/WFC image and the distribution of near-IR H_2 emission (Fig. 1, right). In particular, the southern edge of the "equatorial" H_2 emission (that is, the H_2 emission projected along a line nearly perpendicular to the polar lobes) follows the undulations in the southern edge of the dark lane in exquisite detail. Individual H_2 knots to the southeast and southwest of the position of the central star have distinct counterparts in the ACS/WFC image. We conclude that the H_2 and the obscuring dust are spatially coincident; that is, *the* H_2 *emission traces the equatorial plane of the AFGL 2688 system.*

As the near-infrared H_2 emission east and west of the central star is, evidently, confined to the equatorial regions of AFGL 2688, we conclude that a kinematical model invoking pure radial outflow cannot explain the large-scale east-west velocity gradient previously measured in this and other molecular tracers (wherein emission to the east of the star is predominantly blueshifted, and emission to the west predominantly redshifted; Cox et al. 2000, Kastner et al. 2001, and references therein). Alternative models must be considered. It is conceivable, for example, that the equatorial H_2 and CO emission traces molecular jets, or "bullets," that are initially directed radially outward along the equator of the system and then are redirected toward and away from the observer on the east and west sides of the central star, respectively, by density gradients within the dusty torus. We note, however, that new H_2 and CO velocity mapping observations of AFGL 2688 at superior spatial resolution (P. Cox, these proceedings) must be carefully analyzed to determine the detailed structure of the equatorial kinematics.

3. Peak A: an Accreting White Dwarf?

We propose that the apparent companion to the central star of AFGL 2688 ("Peak A"; Weintraub et al. 2000) — if it is indeed a self-luminous object — may be an accreting white dwarf (WD) which has undergone one or more thermonuclear bursts. This companion cannot have influenced the formation of bipolar structure in the Egg, as this process requires a close ($a \lesssim 50$ AU) binary system. Thus Peak A, at a projected orbital separation of $a \approx 500$ AU, most likely would constitute a tertiary member of the progenitor system.

To evaluate the possibility that Peak A is an accreting WD, we first demonstrate that the mass accretion rate by a WD companion at such an orbital separation can provide the requisite mass for a thermonuclear burst(s). At such large separations the relative velocity between the accreting companion and the wind, v_r, is very nearly the speed of the slow wind, v_s, where $v_s \approx 10$ km s^{-1} along the equatorial plane of AFGL 2688 (Kastner et al. 2001). It is reasonable

to scale the WD mass assuming $M_{\rm WD} \gtrsim 0.6 M_\odot$, as lower mass WDs result either from lower mass stars — which is unlikely for the expired companion to the central star of the Egg Nebula — or from binary interaction. The Bondi-Hoyle accretion rate is then

$$\dot{M} \simeq 10^{-8} \left(\frac{M_{\rm WD}}{0.6\,M_\odot}\right)^2 \left(\frac{v_s}{10\,{\rm km\,s^{-1}}}\right)^{-4} \left(\frac{a}{500\,{\rm AU}}\right)^{-2} \left(\frac{|\dot{M}_1|}{10^{-4}\,M_\odot\,{\rm yr}^{-1}}\right) M_\odot\,{\rm yr}^{-1}.$$

The present mass loss rate of the central, illuminating (F supergiant) star is expected to be well below $\dot{M}_1 = 10^{-4}\,M_\odot\ \ {\rm yr}^{-1}$. However, in our scenario the accreting WD went through a burst in the last < 300 yr. Because there is a time delay between a mass loss epoch and the accretion epoch of that mass, which for the scaling used above is $t_d = a/v_s = 240$ yr, and the F supergiant left the AGB ~ 200 years ago (Jura & Kroto 1990), the WD could still be accreting at present.

A WD of mass $M_{\rm WD} = 0.6 M_\odot$ that accretes at a rate of $\sim 10^{-9}$ to $10^{-8}\,M_\odot\ \ {\rm yr}^{-1}$ will undergo a thermonuclear burst after accreting a mass of $\sim 10^{-4}\ M_\odot$ (e.g., Fujimoto 1982; Iben 1982; Prialnik & Kovetz 1995). From the equation above we find that the Peak A star could have accreted $\sim 10^{-4}$ of the mass lost by the progenitor of the Egg Nebula. For an envelope mass of $\sim 1\ M_\odot$ on the upper AGB, when the wind speed is low enough to enable substantial accretion, we find the total accreted mass to be $\sim 10^{-4}\ M_\odot$, as required for the burst to occur. We conclude that the Peak A star, if a WD, has plausibly gone through at least one burst. Further details concerning this model will be presented in Kastner & Soker (2003, in preparation).

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